Generic calibration procedures for nacelle-based profiling lidars

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GENERIC CALIBRATION PROCEDURES FOR NACELLE-BASED PROFILING LIDARS

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Summary

In power performance testing, it has been demonstrated that the effects of wind speed and direction variations over the rotor disk can no longer be neglected for large wind turbines [1]. A new generation of commercial nacelle-based lidars is now available, offering wind profiling capabilities. Developing standard procedures for power curves using lidars requires assessing lidars measurement uncertainty that is provided by a calibration. Based on the calibration results from two lidars, the Avent 5-beam Demonstrator and the Zephir Dual Mode (ZDM), we present in this paper a generic methodology to calibrate profiling nacelle lidars.

1. Introduction

1.1 Use of profiling lidars to assess power performance

It is now commonly accepted that ground-based profiling LIDARs can improve power performance assessment by measuring simultaneously at different heights [1]. On the other hand, although they are unable to measure wind shear, studies of two-beam nacelle lidars show promising capabilities in assessing power performance [2]. Their use could remove the need to erect expensive meteorology masts, especially offshore. A new generation of commercially developed profiling nacelle lidars combines the benefits of both (Fig. 1).

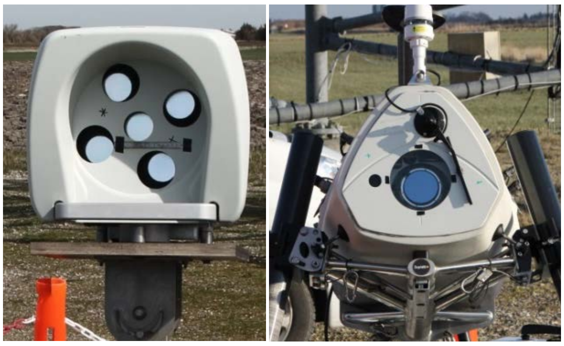

Fig. 1 Left: 5-beam Demonstrator (Avent Lidar Technology), right: ZephIR Dual Mode (ZephIR lidar)

1.2 The need for calibration procedures

The fundamental reason for developing calibration procedures is to assign uncertainties to lidar wind measurements. Commercial applications of lidars, e.g. power performance testing or resource assessment, demand the estimation of measurement uncertainties.

Metrology standards [4] define a calibration as a 3-step process:

- Establishing a relation between the measurand and reference quantity value;
- Derivation of uncertainties on the measurand using both the reference measurement uncertainty and calibration process components;
- Applying the calibration relation to preserve traceability in the measurement chain.

Calibration procedures for two-beam pulsed lidars [3] already exist. We have developed new procedures for profiling nacelle lidars. They are applicable to both pulsed and continuous wave (CW) lidars, irrespective of the geometry of the scanning pattern, and are therefore generic.

2. Calibration procedure principles

2.1 Levels of measurands in a lidar

Understanding the basic principles of lidars is essential to develop adequate calibration procedures. A lidar probes the wind by emitting light through a laser beam. Aeorosols contained in the atmosphere scatter part of the laser light back to the lidar.

One can distinguish three levels of measurands in a lidar. The “rawest” one is the time domain of electrical current induced by the backscattered light on which spectral analysis is performed. The Doppler spectra generated then yield the Doppler frequency. The line-of-sight (LOS) velocity – or Radial Wind Speed (RWS) – is directly proportional to the Doppler frequency. Finally, algorithms combine RWS measurements to derive reconstructed wind parameters, e.g. wind speed and direction, shears, veers, etc.

Considering these levels of measurands, two different calibration concepts can be identified: the black box directly calibrates a reconstructed output whereas the white box refers to calibrating the algorithms’ input quantities.

2.2 Black box calibration concept

A black box calibration is a direct comparison of the reconstructed output with the reference measurand, e.g. horizontal wind speed from a cup anemometer.

The method has the advantages of being fast and relatively easy to implement, since no information is required about the raw measurement post processing and the reconstruction algorithm (the lidar system is considered as a black box).

However, some limitations must be mentioned. First, each reconstructed output should be calibrated; hence multiple calibrated instruments are needed (e.g. how would the vertical shear be measured by a reference instrument?). Next, the reconstructed output does not physically exist as it is derived from a number of RWS measurements distant in space and time.

The wind speed calibration of ground-based lidars is an example of a black box calibration.

2.3 White box calibration concept

The reconstruction algorithms combine radial wind speed measurements, beam localisation quantities – e.g. inclination and roll angles of the beam – and the geometry of the scanning pattern. An alternative methodology to the black box consists in calibrating the reconstruction algorithms' inputs. This method will be subsequently referred to as white box calibration.

The white box calibration requires access to the reconstruction algorithms and to be able to:

- calibrate the lidars internal inclinometers, both for the tilting and rolling;
- verify the scanning pattern geometry, e.g. the opening angle between two beams, or cone angle for a circular scanning pattern;
- calibrate the RWS.

2.4 Why choose the white box?

The advantages of the white box are a calibration of a physically existing quantity and a lower sensitivity to assumptions (flow horizontal homogeneity). More importantly, the uncertainty estimation of any reconstructed parameter is theoretically permitted by the white box approach. However, the physical relevance of the reconstructed parameter has to be addressed.

On the negative side, it takes longer to calibrate multi-beam lidars, as each LOS needs to be calibrated. Alternatively, one or two RWS calibrations combined with a model of deviations between beams could be used. It would also be feasible to simultaneously calibrate two or more LOS, depending on the measurement setup. To implement standard calibration procedures of commercial lidars, the reconstruction algorithms will have to be provided to the accredited calibration laboratory.

The white box calibration is a generic method that can be applied to all profiling nacelle lidars, and possibly to all lidars irrespective of their application. The required data are time-averaged (e.g. 10-min) of: calibrated measurements of horizontal wind speed (HWS, e.g. from cup anemometer) and direction (θ, e.g. from sonic anemometer); lidar RWS and beam inclination $\varphi_{physical}$. These data enable a reference equivalent RWS to be obtained by projecting the HWS onto the LOS direction (LOS_{dir}):

$$Ref_{eq\ RWS} = HWS \cdot \cos(\varphi_{physical}) \cdot \cos(\theta - LOS_{dir})$$

2.5 Main steps of the RWS calibration

The main steps of the RWS calibration are:

a. **<u>Geometry verification</u>**: the parameters characterizing the geometry of the scanning pattern must be measured in order to check the manufacturer's specifications, e.g. cone angle. Knowing the geometry, and assessing its uncertainty, is necessary for reconstructing wind parameters. These values are also used for instance to correctly configure the measurement range of the lidar during the calibration.
b. **<u>Inclinometers calibration</u>**: to know accurately the beam position (see 2.6) and assign uncertainties to the inclination angle φ involved in the vertical projection of the reference HWS.
c. **<u>RWS field measurements</u>**: measurement data collection, with the lidar beam carefully positioned close to a reference instrument.
d. **<u>RWS uncertainty assessment</u>**: combining uncertainties from the reference and measurement process.
e. **<u>Reconstruction of wind parameters</u>**: by combining LOS velocities.
f. **<u>Reconstructed parameters uncertainty assessment</u>**: for instance using the GUM, or any other relevant uncertainty derivation method (e.g. Monte-Carlo or bootstrap).

2.6 Measurement setup

A typical measurement setup for the data collection is described in [3]. Formally, the calibration setup must replicate as closely as possible the measurement conditions in which the lidar will be measuring. For nacelle-lidars, this implies a next-to-horizontal LOS. The lidar beam points towards a mast that is mounted with reference instruments to provide both wind speed and direction (Fig. 2).

Fig. 2 Calibration measurement setup of ZDM (left) and the 5-beam Demonstrator (right), DTU Wind Energy test site, Høvsøre (DK)

Hard target techniques were used to locate the beam accurately. Indeed, the beam must be located close enough to the reference instruments to ensure maximum correlation and minimise bias due to both vertical and horizontal shear (Fig. 3).

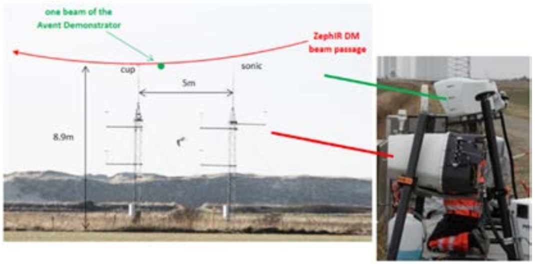

Fig. 3 ZDM (red) and 5-beam Demonstrator (green) beam positions, DTU Wind Energy test site, Høvsøre (DK)

3. Data analysis and calibration results

3.1 LOS direction evaluation

The LOS direction is estimated via data analysis, in two steps. First, an approximate value is obtained by determining the RWS response as a function of wind direction. The fitting functions are of cosine and rectified cosine types for pulsed and homodyne CW lidars, respectively (Fig. 4). In a second step, a number of linear regressions between the RWS and $Ref_{eq\ RWS}$ using different projection angles (LOS_{dir}) are performed. The residual sum of squares (RSS) is reported for each least-square regression. A 2[nd] order polynomial is fitted to the obtained curve. The accurate LOS direction corresponds to the minimum of the parabola (Fig. 5).

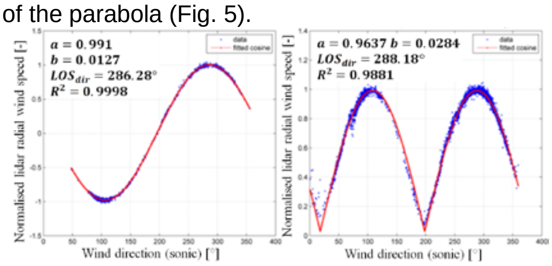

Fig. 4 Cosine and rectified cosine of the 5-beam Demonstrator (left) and ZDM (right)

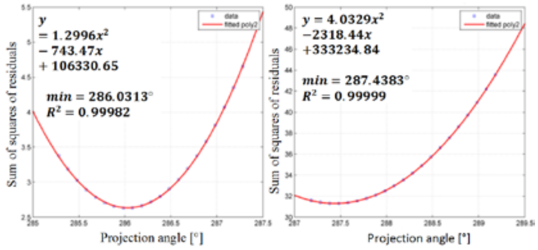

Fig. 5 LOS direction evaluation using the RSS process: 5-beam Demonstrator (left) and ZDM (right)

Fig. 5 shows a difference of $\sim 0.3 - 0.7°$ between the LOS direction and its first estimation in Fig.4.

3.2 Calibration relation: raw and binned linear regressions

The reference equivalent RWS ($\mathrm{Ref}_{\mathrm{eq\ RWS}}$) is now derived and compared to the lidar indicated RWS. Forced and free regressions are performed on both:

- 10-min averaged RWS and $Ref_{eq\ RWS}$ after filtering. A non-exhaustive list of filters is RWS availability, wind direction sector (centered on LOS direction), flow tilt, etc.
- Corresponding bin averages, for 0.5 m/s wide bins and a minimum of 3 points / bin

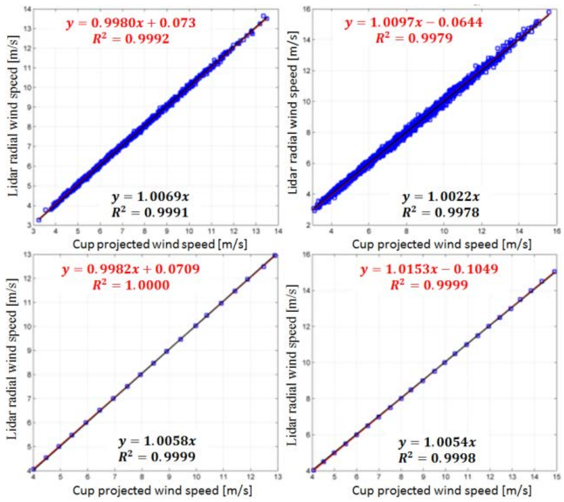

Fig. 6 Calibration relation results of the 5-beam Demonstrator (left) and ZDM (right) lidars: raw (top) and binned (bottom) linear regressions

Fig. 6 shows the calibration results using the top-mounted cup anemometer for HWS and sonic anemometer for wind direction measurements.

Each LOS of the 5-beam Demonstrator has been calibrated. For each of the 5 forced regressions on binned data, R^2 coefficients are all > 0.9999 and the gains vary between 1.0056 and 1.0090.

The ZDM lidar estimates ~ 50 LOS velocities per second. The closest azimuth sector to the reference instruments was used to obtain 10-min averaged LOS velocities. For ZDM, the forced regression results are: $R^2 = 0.9998$ and $gain = 1.0054$.

The calibration results show consistent gains in the forced regression with an error of less than 0.9% for both the ZDM lidar and the five LOS of the Avent lidar. However, the larger variability in the gains and offsets of the free regressions requires further investigation.

4. RWS calibration uncertainty sources

Different measurement uncertainty evaluation methods exist. We have chosen to apply the GUM ("Guide to the expression of Uncertainty in Measurement").

4.1 Uncertainty definition and types

The VIM [4] is a standard document that provides definitions of metrological terminology. The VIM defines uncertainty as a "*non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used*". Two types of uncertainty components are usually considered: type A uncertainties are estimated via statistical tools, whereas other means lead to type B uncertainties. In terms of RWS calibration, type A uncertainties correspond to the variability of the measurements under repeatable conditions.

It should be noted however that atmospheric conditions are not controllable and therefore repeatable conditions do not formally exist in wind energy measurements.

4.2 Reference instrument(s) uncertainties

The **uncertainties of the HWS** measured by the cup anemometer follows IEC 61400-12-1 procedures. The different sources are:

- Wind tunnel calibration uncertainty (type B)
- Operational uncertainty (type B)
- Mounting uncertainty (type B)

The **uncertainty of the wind direction** (type B) measured by the sonic anemometer is taken from the calibration certificate.

4.3 Calibration process uncertainties

Measurement uncertainty sources in the calibration process are:

- **LOS direction uncertainty** (type B), roughly estimated to $0.2°$
- **Beam positioning uncertainty** (type B)
    - Uncertainty of physical beam inclination
    - Beam height uncertainty resulting in wind speed deviations. If a power law shear profile (exponent $\alpha \approx 0.2$) is used, for a height uncertainty of $\Delta H = 10cm$ at $H = 8.9m$:

$$u_{height} = \alpha \cdot \frac{\Delta H}{H} \cdot HWS \approx 0.23\% \cdot HWS$$

- **Statistical uncertainty in the RWS measurement** (type A)

4.4 Combined and expanded uncertainties

All the uncertainty components in the previous sections are expressed for a coverage factor $k = 1$ (i.e. u corresponds to the half width of a 68% confidence interval for a normal distribution).

Using the reconstruction algorithms, RWS are combined. The GUM methodology is then applied to the reconstruction equations, generating the combined uncertainty U_c on the reconstructed parameter (see [3] for an example on HWS from 2-beam lidars). Finally, the expanded uncertainty is obtained by multiplying the combined uncertainty by the desired coverage factor, e.g. $k = 2$ (half-width of 95% confidence interval).

5. Discussion

Previous studies on the calibration of two-beam nacelle lidars have shown that calibrating the inputs of the reconstruction algorithms of lidars was possible. The studies also demonstrated that the RWS field calibration provides consistent results. However, the procedures were specific to two-beam pulsed nacelle lidars. It was therefore necessary to adapt them in order to be applicable to any type of lidar and thus become generic.

In this paper, two possible calibration concepts for nacelle-based profiling wind lidars have been identified. The preferred approach is the white box calibration, which, by using the derived RWS uncertainties allows estimation of uncertainties of any reconstructed parameter. The calibration procedures were applied to both a pulsed multi-beam lidar and a CW lidar.

Calibrations results have proven to be satisfactory in both cases with a high level of agreement between the lidars' RWS and the reference measurements, confirming the feasibility of the RWS calibration. The methodology is generic and could therefore form the scientific basis of standardised nacelle lidars calibration procedures.

However, some limitations must be mentioned. First, the uncertainty components from the reference instrument are predominant, highlighting the need for better calibration procedures of cup anemometers. Second, the measurement setup is not ideal because of high turbulence intensity at low heights. On the other hand, a tall mast would require the lidar to be installed on an expensive stiff platform to avoid adding significant measurement uncertainties. Finally, in the white box calibration, having access to reconstruction algorithms is mandatory.

Further work will involve sensitivity analysis of the RWS calibration results to e.g. atmospheric parameters or quantity of valid measurement data. After defining new custom reconstruction algorithms, uncertainties will be derived on the reconstructed outputs.

6. References

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